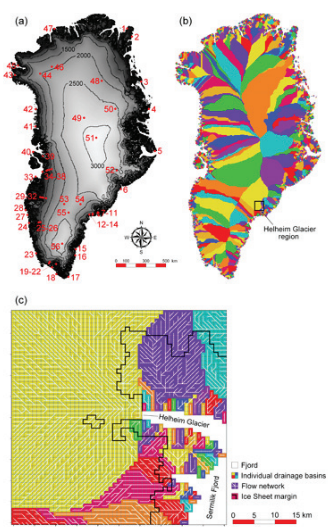
Spatial Freshwater Runoff Distribution from Greenland, 1960–2010

Sebastian H. Mernild, CCS-2

HydroFlow, a gridded runoff routing model, was developed to simulate the linkages between runoff production from land-based snow and ice-melt processes and the associated freshwater fluxes to downstream areas and surrounding oceans. HydroFlow was specifically designed to account for ice sheet, glacier, and snow-free and snow-covered land applications. As part of its discharge simulations, HydroFlow creates a flow network that links the individual grid cells that comprise the simulation domain. Runoff magnitudes, the spatial patterns from individual Greenland catchments, and their changes through time (1960–2010) were simulated in an effort to understand runoff variations and trends to adjacent seas. Total Greenland runoff to the surrounding oceans increased 30%, averaging 481±85 km^3 per year. Averaged over the period, 69% of the runoff to the surrounding seas originated from the Greenland Ice Sheet and 31% came from outside the ice sheet from melting glaciers and ice caps. Regionally, runoff was greater from western than eastern Greenland.

Fig 1. (a) Greenland with topography (500-m contour interval) and the location of the coastal and GrIS meteorological tower stations (red dots). HydroFlow simulations were performed for Greenland using a 5-km grid increment and daily time step from September 1959–December 2010, forced with observed atmospheric data from 56 meteorological stations located in coastal areas and on the ice sheet. The ice sheet is shaded from gray to white by elevations, with the area outside the ice sheet in black. (b) Simulated individual Greenland drainage basins (represented by multicolors). Also, a specific region is illustrated (see bold square). (c) A close-up example of the individual drainage basins and flow network for the Helheim Glacier region, at the innermost part of the Sermilik Fjord, SE Greenland.



Long-term temperature observations show warming trends of variable strength throughout the Arctic, and ample evidence indicates that the Arctic hydrological cycle, including that for Greenland and the Greenland Ice Sheet, is changing [1-3]. Since the early 1990s, the increase in ice sheet surface runoff has followed atmospheric warming, explaining half of the recent mass loss of the Greenland Ice Sheet [4] —a mass loss that by 2100 may contribute up to a 54-cm sea-level equivalent (SLE) [5] because model simulations of future scenarios point to higher temperatures [2,6]. In addition to the sea level contribution, terrestrial runoff from Greenland is important for ocean density and thermohaline circulation [7], specifically to the Atlantic Meridional Overturning Circulation (AMOC) and its impact on the climate system [8].

HydroFlow is a spatially distributed model that divides the simulation domain into individual drainage basins, linking each grid cell within each drainage basin via an eight-compass-direction waterflow routing network. As part of the flow network generation, only a single flow outlet into the ocean is allowed for each individual watershed. The waterflow is transported through the gridded routing network via linear reservoirs, and conservation of mass principles between inflow, storage change, transit times, and outflow from each cell in the routing network must be defined to simulate the catchment runoff and generate discharge hydrographs for the routing grid cells. For runoff routing, HydroFlow assumes the existence of different transport mechanisms within each individual model grid cell: 1) a slow-response runoff system, representing the time it takes for any available snow and ice melt, including liquid precipitation, to be transported within a model grid cell to the fast-response reservoir; and 2) a fast-response system representing flow processes such as those represented by water transport over, inside, and below the ice that moves water down-network. As part of the modeling system, locally generated runoff from snow-covered ice, snow-free ice, snow-covered land, and snow-free land are all associated with different residence times that evolve with time as the snow and ice melt [9].

HydroFlow divided the ice sheet into approximately 400 individual drainage basins, and Greenland into approximately 3,150 individual basins, where the drainage basins range in area from 50 km^2 to 154,800 km^2 (Fig. 1), with 85% of the drainage basins equal to or less than 250 km^2—these relatively small basins cover 10% of the total Greenland area, and are mainly located in the land area between the ice sheet and the oceans.

Time series (1960–2010) of Greenland Ice Sheet surface hydrological conditions of net precipitation (precipitation minus evaporation and sublimation), surface runoff, and surface mass balance are shown in Fig. 2. The average 1960–2010 simulated ice sheet net precipitation was 489±53 km^3 per year, varying on a decadal scale from 456±46 km^3 per year in 1960–1969 to 516±38 km^3 per year in 2000–2010. The ice sheet average runoff was 333±75 km^3 per year, varying from 261±75 km^3 per year in 1970–1979 to 429±57 km^3 per year in 2000–2010. For the period 1960–2010, the Greenland Ice Sheet net precipitation and surface runoff rose significantly, leading to a significantly enhanced surface mass loss. Even with an enhanced surface mass loss, the average annual surface mass balance was 156±82 km^3 per year (1960–2010), varying from 220±86 km^3 per year in 1970–1979 to 86±72 km^3 per year in 2000–2010. These surface conditions closely follow air temperature

For more information contact Sebastian H. Mernild at mernild@lanl.gov.

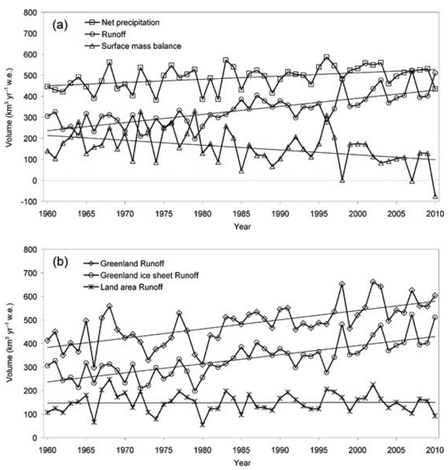


Fig. 2. (a) Greenland Ice Sheet simulated net precipitation, surface runoff, and surface mass balance time series for 1960–2010. (b) Simulated surface ice sheet runoff, land strip area (area outside the ice sheet) runoff, and Greenland runoff time series for 1960–2010.

fluctuations, indicating that surface mass loss increased as climate warmed with no suggestion of deceleration.

Time series of Greenland runoff (1960–2010) and individual runoff contributions from the ice sheet and from the land area–including thousands of glaciers and ice caps–located between the ice sheet and the surrounding oceans are shown in Fig. 2b. The 1960–2010 average simulated Greenland runoff was 481±85 km^3 per year, indicating that 69% of the runoff to the surrounding seas originated from the ice sheet and 31% from the land area. For the land area, the trend in runoff was constant, and the average runoff was 148±41 km^3 per year.

For Greenland, the spatial distribution of surface runoff is illustrated for the decade with the lowest (1970–1979) and highest (2000–2010) runoff, and for 1960–2010 (Fig. 3). Generally, relatively high average surface runoff values were simulated for the southwest and southeast regions of Greenland, and sporadic high values were simulated in the north region with maximum values of 4–6 m w.e. per year. Elsewhere runoff was less, with lowest values in the northeast and northwest regions of less than 0.5 m w.e. per year. This regional pattern in surface runoff can be largely explained by the spatial distribution of precipitation, since snowfall (end-of-winter accumulation) and surface runoff are negatively correlated through surface albedo, snow depth, and snow characteristics (e.g., snow cold content) [1,10,11].

In Fig. 4, the spatial runoff distribution from Greenland to the adjacent seas is illustrated. The 1960–2010 average discharge for these drainage catchments varied from <0.01 km^3 per year to 10.1 km^3 per year. The spatial variability in catchment runoff to the surrounding seas varied according to catchment size, ice sheet and glacier elevation range, and ice sheet and glacier areal coverage within each individual catchment. For approximately half of the catchments (colored radial bars), runoff amounted to less than 1.0 km^3 per year (1960–2010), collectively contributing 15% of the 481-km^3-per-year total Greenland runoff. In contrast, 15% of the catchments–catchments having a relatively large ice sheet and/or glacier areal coverage–had a mean annual runoff greater than 2.5 km^3 per year and contributed 40% of the Greenland runoff to the adjacent seas. Greenland was further divided into eight 45-degree regions. Regionally, the average Greenland 1960–2010 simulated runoff to the adjacent seas was greatest from sectors S (88 km^3) and SW (82 km^3), and lowest from sectors E (45 km^3) and SE (49 km^3). The length of the discharge season at regional scales was highest in the southern sectors (averaging approximately 4–6 months) and lowest in the northern sectors (averaging approximately 2–3 months).

Fig. 3. Simulated Greenland spatial surface runoff for the decade with the lowest (1970–1979) and highest (2000–2010) runoff, and the 50-year mean (1960–2010).

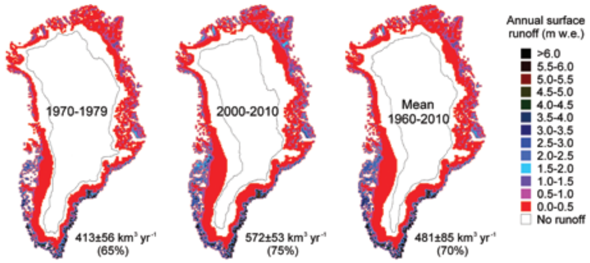
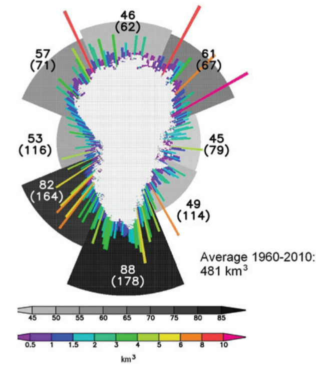


Fig. 4. Spatial distribution of simulated runoff from Greenland's individual drainage basins (each radial colored bar represents the accumulated runoff of ten catchments located side by side [in total there are 316 radial bars]; this was done to simplify the presentation of spatial runoff trends, since 85% of all catchments are equal or below 250 km²), and from the eight sectors (N, NE, E, etc.), to the adjacent seas: mean annual Greenland runoff for 1960–2010. The numbers in parentheses indicate the length of the discharge season for each region.



[1] Ettema, J. et al., *Geophys Res Lett* **36,** L12501; doi:10.1029/GL038220 (2009).
[2] Mernild, S.H. et al., *J Hydrometeorology* **11,** 3 (2010).
[3] Mernild, S.H. et al., *J Climate* **24,** 609; doi: 10.1175/2010 JCLI3560.1 (2011).
[4] Van den Broeke, M.R. et al., *Science* **326,** 984 (2009).
[5] Pfeffer, W.T. et al., *Science* **321,** 1340 (2008).
[6] Solomon, S.D. et al., Eds., *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press, Cambridge, UK and New York, NY, USA (2007).
[7] Rahmstorf, S. et al., *Geophys Res Lett* **32,** L23605; doi:10.1029/2005GL023655 (2005).
[8] Bryden, H.L. et al., *Nature* **438,** 655; doi:10.1038/nature04385 (2005).
[9] Mernild, S.H. and G.E. Liston, *J Climate,* accepted (2012).
[10] Hanna, E. et al., *J Climate* **21,** 331 (2008).
[11] Mernild, S.H. et al., *Hydrolog Process* **23,** 2470; doi: 10.1002/hyp.7354 (2009).

Funding Acknowledgments
LANL Institute for Geophysics and Planetary Physics Fellowship; LANL Director's Postdoctoral Fellowship